SYNCHRONOUS MOTOR DESIGN AND ANALYSING THE OUTPUT CHARACTERISTICS

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ABSTRACT

AC Synchronous Motors range in size from sub-fractional horsepower to over 10,000 horsepower. Smaller synchronous motors can be found in household devices such as clocks, timers, fans and cassette players, and as stepper motors in computer disk drives and printers. Larger synchronous motors are used in process industries and drive equipment such as compressors. Large synchronous motors most commonly employ a three-phase system. The smaller AC Synchronous Motors commonly use a single-phase system. Synchronous motor is consists of two parts those are stator and rotor. Stator is stationary part that produces rotating magnetic field and then, the rotor locks into step with rotating magnetic field. This paper focuses on uses the permanent magnet on rotor shaft to produce magnetic field instead of uses slip rings and carbon brush to supply external dc source to the shaft. Permanent magnet synchronous motor is also called brushless because the excitation flux is produced by permanent magnet. Application of neodymium-iron-boron ($Nd_2Fe_{14}B$) and samarium cobalt (Sm_1Co_5 and Sm_2Co_{17}) rare earth magnets results in high torque and power density, efficiency, and controllability, reliability, and ruggedness. The synchronous motor has the same physical stator as induction motor. Then the output of two type of motor can be analyse and compared the result. The output that should be considered is frequency, rpm, torque, hp, losses, and efficiency. From this project we can use the spec of induction motor to guide in design basic principal of synchronous motor with the same spec. Through of this some of development should be done to improve the efficiency and reliability of the motor.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Synchronous motors are like induction motor in that they both have stator windings to produce a rotating magnetic field. Unlike an induction motor, the synchronous motor is excited by an external DC source and therefore requires slip rings and brushes to provide current to the rotor and produce magnetic field.

An AC Synchronous Motor rotates at a fixed speed, despite of any increase or decrease in load. The motor will keep its fixes speed until the torque required reaches its pull out torque (maximum torque). If the load becomes greater then reach motor's pull out torque, the AC Synchronous Motor will not slow down because it reaches a point at which it will stall and stop turning. The pull-out torque is generally 1.5 times the continuously rated torque.

The AC Synchronous motor is an effective way to obtain a fixed speed at a very low motor system cost. No expensive driver or amplifier is necessary. Most synchronous motors are used where precise timing and constant speed are required.

AC Synchronous Motors range in size from sub-fractional horsepower to over 10,000 horsepower. Smaller synchronous motors can be found in household devices such as clocks, timers, fans and cassette players, and as stepper motors in computer disk drives and printers. Larger synchronous motors are used in process industries and drive equipment such as compressors. Large synchronous motors most commonly employ a three-phase system. The smaller AC Synchronous Motors commonly use a single-phase system. The three-phase AC Synchronous Motor is the focus of this paper. Synchronous motors have the following advantage over non-synchronous motor.

i. Speed is independent of the load, provided an adequate field current is applied.
ii. Accurate control in speed and position using open loop controls, eg. stepper motors.
iii. They will hold their position when a DC current is applied to both the stator and the rotor windings.
iv. Their power factor can be adjusted to unity by using a proper field current relative to the load. Also, a "capacitive" power factor, (current phase leads voltage phase), can be obtained by increasing this current slightly, which can help achieve a better power factor correction for the whole installation.
v. Their construction allows for increased electrical efficiency when a low speed is required (as in ball mills and similar apparatus).

1.1.1 Basic construction and operating principle

Three phase AC synchronous motor are commonly used in industrial applications. This type of motor has three main parts, rotor, stator, and enclosure. The stator and rotor do the work and the enclosure protects the stator and rotor.

To understand how the synchronous motor works, assume that the application of three-phase ac power to the stator causes a rotating magnetic field around the rotor. The rotor is energized with dc (it acts like a bar magnet). The strong rotating magnetic field attracts the strong rotor field activated by dc. This results in a strong turning force on rotor shaft. Therefore enable rotor to turn a load as it rotates in step with rotating magnetic field.

1.1.2 Stator

The stator is the stationary part of the motor electromagnetic circuit. The stator is made up of several thin laminations of aluminium or cast iron. Laminations are used to reduce energy losses that would result if solid core is used. They are punched and clamped together to form a hollow cylinder.

Stator laminations are stacked together forming hollow cylinder. Coils of insulated wire are inserted into slots of stator core. When the assembled motor is in operation the stator winding are connected directly to the power of source. Each grouping of coils, together with the steel core it surrounds, become and electromagnet when current is applied. Electromagnetism is the basic principle behind motor operation.

1.1.3 Rotor

The rotor is the rotating part of the motor electromagnetic circuit. Most of motor commonly used brush-type rotor that uses slip rings for application of DC field current to produce magnetic field on rotor. Low voltage DC is used for the rotating field 120 VDC and 250 VDC are typical. The other type of rotor is rotor permanent magnet. For this type rotor is completely independent form any external source.

1.1.4 Enclosure

The enclosure consists of a frame (or yoke) and two ends bracket (bearing housings). The stator is mounted inside the frame. The rotor fits inside the stator with slight air gap separating it from the stator. There is no direct physical connection between the rotor and the stator. The enclosure protects the internal parts of the motor from water and other environment elements. The degree of protection depend the type of enclosure. Bearing mounted on the shaft, support the rotor and allow it to turn. Fan also mounted on rotor shaft to cool the motor when the shaft is rotating.

1.2 PROBLEM STATEMENT

The problem is to produce magnetic field on the rotor side. The magnetic field can define by use

i. Slip ring and brushes
   - The use of slip ring and brush need more concern about maintenance

ii. Permanent magnet
   - Instead of using slip ring and brush the magnetic field on rotor can replace by use of permanent magnet

Advantage of using permanent magnet

- Less maintenance than slip ring and brushes
- Completely independent from any external source
- Brush voltage drop can be the cause of power loss on machines with larger field currents

For this synchronous motor is referring to use permanent magnet shaft. Figure 1.1 below shows the synchronous motor block diagram.

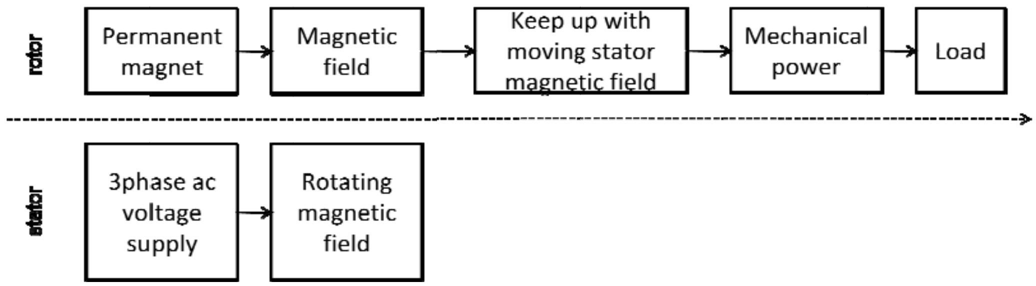


Figure 1.1: Synchronous motor block diagram

1.3 PROJECT OBJECTIVE

The objective of this project is to:

i. Design the basic principal of synchronous motor.
ii. Analyze the output characteristics
iii. Understand the concept of design synchronous motor

1.4 SCOPE OF PROJECT

This project concentrates of using permanent magnet to produce magnetic field in rotor part instead of use slip rings and brushes. The spec that should be considered is

i. The desire output =approximately ½ hp(373W)
ii. Supply input voltage=415V,3Φ
iii. Input current=0.90A

CHAPTER 2

THEORY AND LITERATURE REVIEW

2.1 Introduction

AC motor is worldwide use in many applications. It is transform from electrical energy into mechanical energy. There are many types of ac motor, but this project focusing on the three phase ac synchronous motor. Build without complex electronic control, synchronous motor is inherently constant speed motors. They operate absolutely synchronize with line frequency.

In this chapter the researcher will view more about the synchronous motor including the theory, operation, construction

2.2 Permanent magnet synchronous motor

The PM Synchronous motor is a rotating electric machine where the stator is a classic three phase stator like that of an induction motor and the rotor has surface-mounted permanent magnets. In this respect, the PM Synchronous motor is equivalent to an induction motor where the air gap magnetic field is produced by a permanent magnet. The use of a permanent magnet to generate a substantial air gap magnetic flux makes it possible to design highly efficient PM motors.

A PM Synchronous motor is driven by sine wave voltage coupled with the given rotor position. The generated stator flux together with the rotor flux, which is generated by a rotor magnet, defines the torque, and thus speeds, of the motor. [1]

2.3 The operation of synchronous motor

A permanent magnet synchronous motor is driven by sine wave voltage coupled with the given rotor position. The generated stator flux together with the rotor flux, which is generated by a rotor magnet, defines the torque, and thus speeds, of the motor. The sine wave voltage output have to be applied to the 3-phase winding system in a way that angle between the stator flux and the rotor flux is kept close to 90° to get the maximum generated torque. To meet this criterion, the motor requires electronic control for proper operation. [2]

In the synchronous motor, the rotor locks into step with the rotating magnetic field and rotates at synchronous speed. If the synchronous motor is loaded to the point where the rotor is pulled out of step with the rotating magnetic field, no torque is developed, and the motor will stop. A synchronous motor is not a self-starting motor because torque is only developed when running at synchronous speed; therefore, the motor needs some type of device to bring the rotor to synchronous speed. [3]

2.4 The winding structure

The windings are connected in wye. The two windings in each phase are wound in the same direction. At any instant in time, the magnetic field generated by one particular phase will depend on the current through that phase. If the current through that phase is zero, the resulting magnetic field is zero. If the current is at a maximum value, the resulting field is at a maximum value. Since the currents in the three windings are 120° out of phase, the magnetic fields produced will also be 120° out of phase. The three magnetic fields will combine to produce one field, which will act upon the rotor. In an AC induction motor, a magnetic field is induced in the rotor opposite in polarity of the magnetic field in the stator. Therefore, as the magnetic field rotates in the stator, the rotor also rotates to maintain its alignment with the stator's magnetic field. [4]

2.5 Stator construction

The stator is the stationary part of the motor. The core of the stator is made up of several hundred thin laminations. These laminations are based on National Electric Manufactures Association (NEMA). Stator laminations are stacked together forming a hollow cylinder and coils of insulated wire are inserted into slot of the stator core. The basic concept of the motor operation is electromagnetism which is, each group of coils together with the steel it surrounds form an electromagnets. The stator winding are connected directly to the power circuit. [5] Figure2.1 below shows the stator case with the winding insulator.

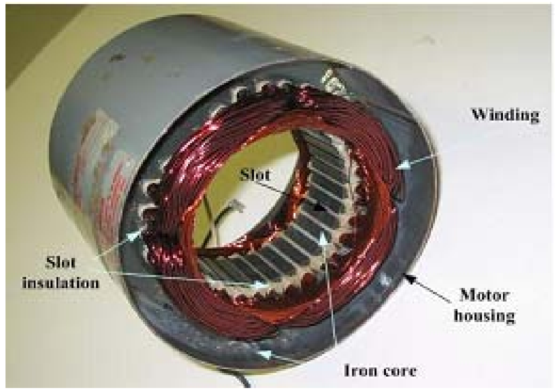


Figure2.1: Stator case with winding

2.6 Starting of synchronous motor

The disadvantage of a synchronous motor is that it cannot be started from a standstill by applying three-phase ac power to the stator. When ac is applied to the stator, a high-speed rotating magnetic field appears immediately. This rotating field rushes past the rotor poles so quickly that the rotor does not have a chance to get started. In effect, the rotor is repelled first in one direction and then the other. A synchronous motor in its purest form has no starting torque. It has torque only when it is running at synchronous speed. A squirrel-cage type of winding is added to the rotor of a synchronous motor to cause it to start. The squirrel cage is shown as the outer part of the rotor in figure 4-7. It is so named because it is shaped and looks something like a turnable squirrel cage. Simply, the windings are heavy copper bars shorted together by copper rings. A low voltage is induced in these shorted windings by the rotating three-phase stator field. Because of the short circuit, a relatively large current flows in the squirrel cage. This causes a magnetic field that interacts with the rotating field of the stator. Because of the interaction, the rotor begins to turn, following the stator field; the motor starts. We will run into squirrel cages again in other applications, where they will be covered in more detail.

To start a practical synchronous motor, the stator is energized, but the dc supply to the rotor field is not energized. The squirrel-cage windings bring the rotor to near synchronous speed. At that point, the dc field is energized. This locks the rotor in step with the rotating stator field. Full torque is developed, and the load is driven. [6]

2.7 The air gap

In the synchronous machine two separate magnetic fields exist in the air gap, supplied from two separate sources. This is referred to as armature reaction-the reaction of the stator field against the rotor field. To minimize this, the air gap must be large enough to keep the ratio of air gap ampere-turns to armature reaction ampere-turns per pole above an empirical limit, often taken as 1.0. The higher that ratio, the less influence of armature reaction and the more sinusoidal the flux waveform under load. For a highly stable machine, a ratio of 2 to 3 may be needed. Hence, for any given rotor diameter, a synchronous machine's air gap may be two or more times that of an induction machine. [7]

2.8 Magnet

Magnets are an important part of our daily lives, serving as essential components in everything from electric motors, loudspeakers, computers, compact disc players, microwave ovens and the family car, to instrumentation, production equipment, and research. Their contribution is often overlooked because they are built into devices and are usually out of sight.

Magnets function as transducers, transforming energy from one form to another, without any permanent loss of their own energy. General categories of permanent magnet functions are:

- **Mechanical to mechanical** - such as attraction and repulsion.
- **Electrical to mechanical** - such as motors, loudspeakers, charged particle deflection.
- **Mechanical to heat** - such as eddy current and hysteresis torque devices.
- **Special effects** - such as magneto resistance, Hall Effect devices, and magnetic resonance.

2.8.1 Modern magnet material

There are four classes of modern commercialized magnets, each based on their material composition. Within each class is a family of grades with their own magnetic properties. These general classes are:

- Neodymium Iron Boron
- Samarium Cobalt
- Ceramic
- Alnico

NdFeB and SmCo are collectively known as Rare Earth magnets because they are both composed of materials from the Rare Earth group of elements. Neodymium Iron Boron (general composition $Nd_2Fe_{14}B$, often abbreviated to NdFeB) is the most recent commercial addition to the family of modern magnet materials. At room temperatures, NdFeB magnets exhibit the highest properties of all magnet materials. Samarium Cobalt is manufactured in two compositions: Sm_1Co_5 and Sm_2Co_{17} - often referred to as the SmCo 1:5 or SmCo 2:17 types. 2:17 types, with higher H_{ci} values, offer greater inherent stability than the 1:5 types. Ceramic, also known as Ferrite, magnets (general composition $BaFe_2O_3$ or $SrFe_2O_3$) have been commercialized since the 1950s and continue to be extensively used today due to their low cost. A special form of Ceramic magnet is "Flexible" material, made by bonding Ceramic powder in a flexible binder. Alnico magnets (general composition Al-Ni-Co) were commercialized in the 1930s and are still extensively used today. [8]

These materials span a range of properties that accommodate a wide variety of application requirements. The following is intended to give a broad but practical overview of factors that must be considered in selecting the proper material, grade, shape, and size of magnet for a specific application. The Table 2.1 shows typical values of the key characteristics for selected grades of various materials for comparison.

Table 2.1: Magnet material comparisons

Material	**Grade**	**Br**	**Hc**	**Hci**	**BHmax**	**T_{max} (Deg C)***
NdFeB	39H	12,800	12,300	21,000	40	150
SmCo	26	10,500	9,200	10,000	26	300
NdFeB	B10N	6,800	5,780	10,300	10	150
Alnico	5	12,500	640	640	5.5	540
Ceramic	8	3,900	3,200	3,250	3.5	300
Flexible	1	1,600	1,370	1,380	0.6	100
* T_{max} (maximum practical operating temperature) is for reference only. The maximum practical operating temperature of any magnet is dependent on the circuit the magnet is operating in.						

2.8.2 Unit of a measure

Three systems of units of measure are common: the cgs (centimetre, gram, second), SI (meter, kilogram, second), and English (inch, pound, second) systems. This Table 2.2 below uses the cgs system for magnetic units, unless otherwise specified.

Table2.2: Units of measure systems

Unit	**Symbol**	**cgs System**	**SI System**	**English System**
Flux	ø	maxwell	weber	Maxwell
Flux Density	B	gauss	tesla	lines/in^2
Magnetomotive Force	F	gilbert	ampere turn	ampere turn
Magnetizing Force	H	oersted	ampere turns/m	ampere turns/in
Length	L	cm	M	In
Permeability of a vacuum	μ_v	1	$0.4\pi \times 10^{-6}$	3.192

2.8.3 Manufacturing method

Permanent magnets are manufactured by one of the following methods:

- Sintering, (Rare Earths, Ceramics, and Alnicos)
- Pressure Bonding or Injection Moulding, (Rare Earths and Ceramics)
- Casting, (Alnicos)
- Extruding, (Bonded Neodymium and Ceramics)
- Calendering (Neodymium and Ceramics)

The sintering process involves compacting fine powders at high pressure in an aligning magnetic field, then sintering to fuse into a solid shape. After sintering, the magnet shape is rough, and will need to be machined to achieve close tolerances. The intricacy of shapes that can be thus pressed is limited. [8]

Rare earth magnets may be die pressed (with pressure being applied in one direction) or isostatically pressed (with equal pressure being applied in all directions). Isostatically pressed magnets achieve higher magnetic properties than die pressed magnets. The aligning magnetic field for die pressed magnets can be either parallel or perpendicular to the pressing direction. Magnets pressed with the aligning field perpendicular to the pressing direction achieve higher magnetic properties than the parallel pressed form. [8]

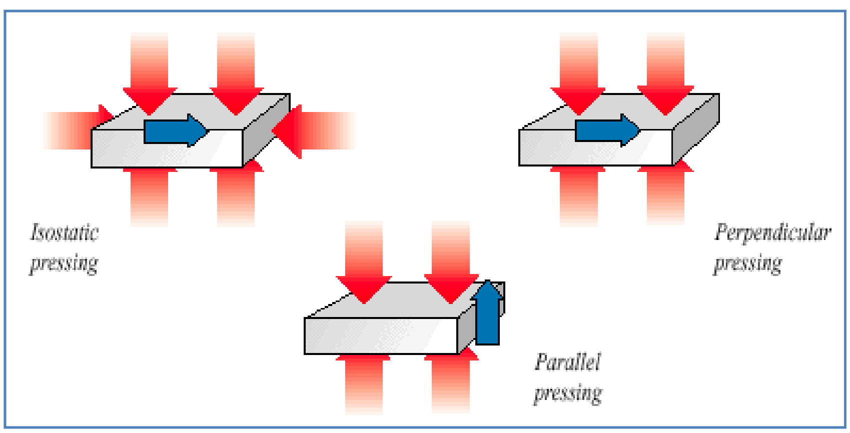


Figure 2.2: Die pressed rare earth magnet

Both Rare Earth and Ceramic magnets can also be manufactured by pressure bonding or injection molding the magnet powders in a carrier matrix. The density of magnet material in this form is lower than the pure sintered form, yielding lower magnetic properties. However, bonded or injection molded magnets may be made with close tolerances "off-tool" and in relatively intricate shapes. [8]

Alnico is manufactured in a cast or sintered form. Alnicos may be cast in large or complex shapes (such as the common horseshoe), while sintered Alnico magnets are made in relatively small sizes (normally one ounce or less) and in simple shapes. [8]

Flexible Rare Earth or Ceramic magnets are made by calendaring or extruding magnet powders in a flexible carrier matrix such as vinyl. Magnet powder densities and therefore magnetic properties in this form of manufacture are even lower than the bonded or injection molded form. Flexible magnets are easily cut or punched to shape. [8]

2.8.4 Flux density

Flux density measurements are made using a gaussmeter and an appropriate probe. The probe contains a Hall Effect device whose voltage output is proportional to the flux density encountered. Two types of probe construction (axial, where the lines of flux traveling parallel to the probe holder, and transverse where the lines of flux traveling perpendicular to the probe holder, are measured) allow the measurement of flux density of magnets in various configurations. The placement of the probe with respect to the magnet is critical in order to obtain comparable measurements from magnet to magnet. This is accomplished by building a holding fixture for the magnet and probe, so that their positions are fixed relative to each other. [8]

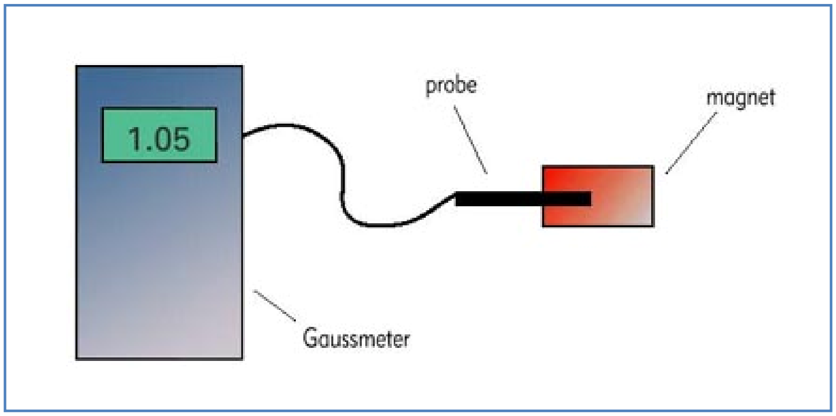


Figure 2.3: Gaussmeter

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter explains more detail about the designing of the three-phase ac synchronous motor according to the three main parts rotor, stator, and enclosure. Each part of the motor should be concern including of the material, shape, size, and availability. Figure 3.1 shows the partially assembled motor.

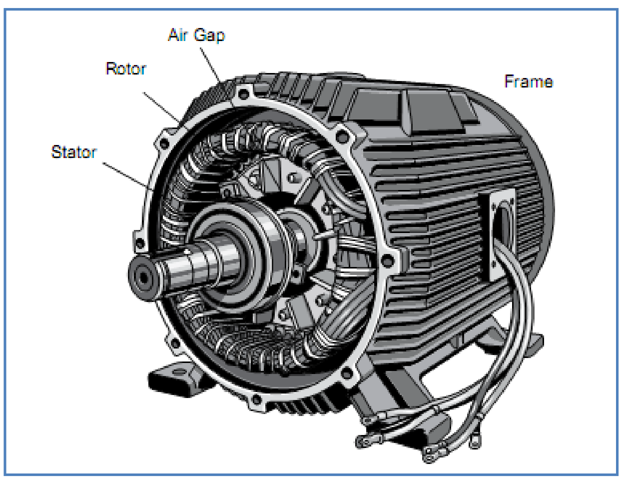


Figure 3.1: Partially assembled motor

3.2 Hardware implementation

3.2.1 Stator coil arrangement

This motor used six winding for electrical configuration of stator winding, two for each of the three phases. The coils are wound around the soft iron core material of the stator. When current applied each winding become electromagnet with one winding is a north pole and the other is south pole. For example in Figure 3.2, when A1 is a north pole, A2 is a south pole and when current is reverse direction, the polarities of the winding also reverse.

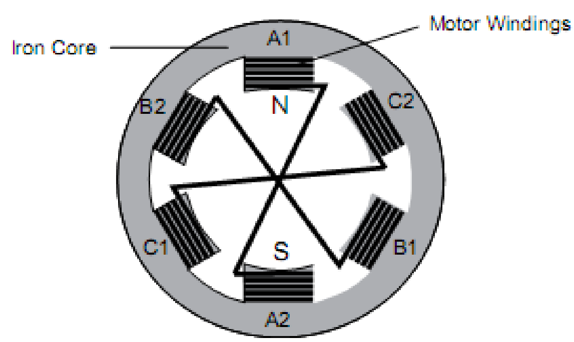


Figure 3.2: Stator coil

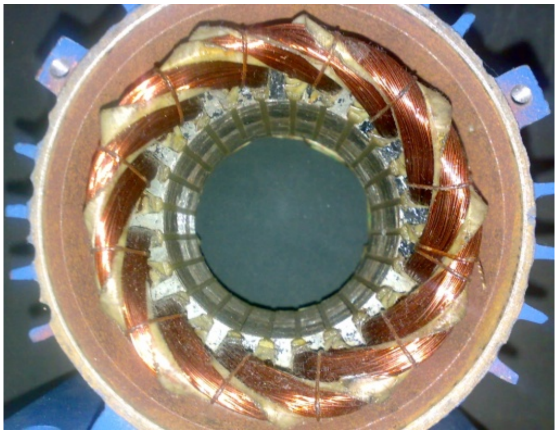


Figure 3.3: The actual stator motor and coil

The stator is connected to a three-phase AC power source. The Figure 3.4 below shows that winding A1 and A2 is connected to phase A of the power supply. When connection completed, B1 and B2 will be connected to phase B, and C1, C2 connected to phase C. Coils A1, B1, and C1 are 120^{o} apart. Also windings A2, B2, and C2 are 120^{o}apart. Number of turn determine according to the same motor of 3 phase ac induction motor with the same spec 0.5 hp.

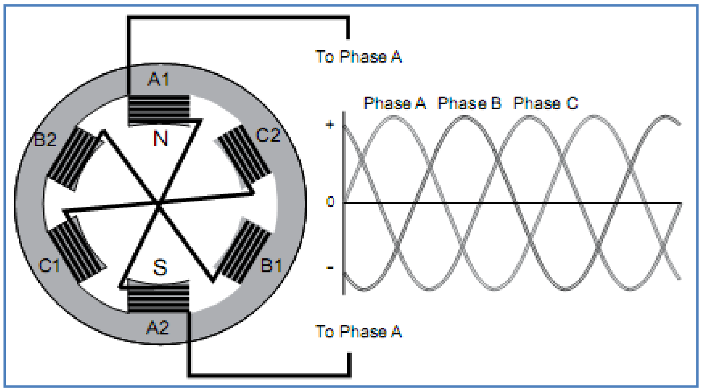


Figure 3.4: Interconnection of winding

3.2.2 Winding insulation

Insulation of the winding is one of the most critical parts in this design. When the insulation breaks down, the machine shorts out. The cost of repair machine with shorted insulation is expensive and sometimes impossible.

The temperature of the winding should be limited to prevent the insulation from breaking down because of the overheating. This can be preventing by providing circulation of cool air over the windings. The continuous power supplied to the machine usually limited by the maximum temperature of winding. The increased in temperature usually degrades the insulation. Life of the machine is halved for a temperature rise of 10 percent above the rate temperature winding.

The temperature limits for machine insulation have been standardized by the National Electrical Manufactures Association (NEMA). A series of insulation system class have been defined. Each insulation system class specifies the maximum temperature allowed. The most common NEMA insulation class for ac motor are A, B, F, and H. Figure 3.5 below shows the higher permissible temperature for each class.

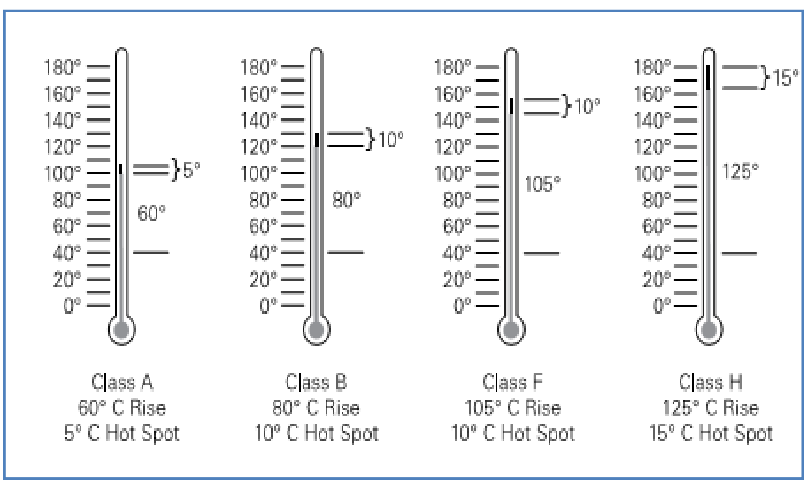


Figure 3.5: Higher permissible temperature for each class

Similar standards have been defined by the International Electrotechnical Commission (IEC) and by other national standard organizations. In this motor prefer used type F insulation class. This type of insulator is the most commonly used for motor. The allowable temperature 105^{o}c rise from ambient temperature 40^{o}c

3.2.3 Rotor construction

The type of rotor used is permanent magnet type. With a permanent magnet mounted on a shaft can be substituted for brush-type shaft with slip ring of rotor. When stator winding are energized, a rotating magnet is established. The magnet has its own magnetic field that interacts with rotating magnetic field of the stator. The north pole of the rotating field attracts the south pole of the magnet, and the south pole of rotating magnetic field attracts the north pole of the magnet. As the magnetic field rotates, it pulls the magnet along.

Figure 3.6 shows the size of designing shaft according to the size of bearing and enclosure. Arch and segment shape permanent magnet shows in figure 3.7 will mounted on rotor shaft. NdFeb rare earth magnet is the type of permanent magnet suitable used to produce strong magnetic field. Figure 3.8 shows the mounted magnet on the rotor shaft.

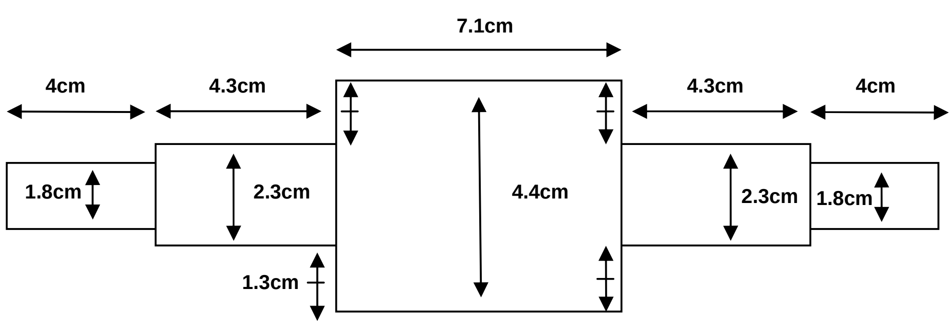
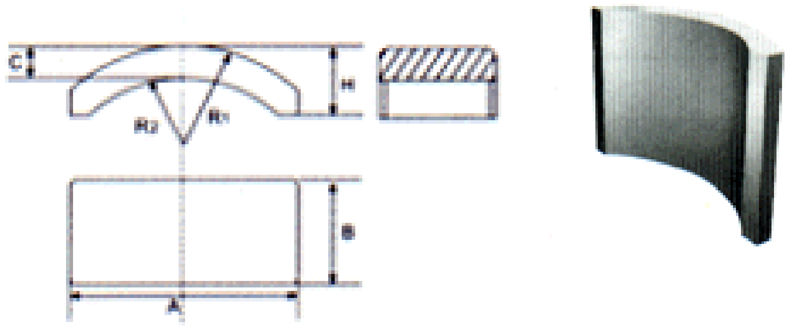


Figure 3.6: Size of designing shaft



R_1= 3.1cm A= 3.8cm C= 1.2cm

R_2= 1.9cm B= 7cm H= 2.1cm

Figure 3.7: Size of magnet

Figure 3.8: Mounted magnet on the rotor shaft

3.2.4 Choosing the Enclosure

A motors enclosure not only holds the motor components together, it also protects the internal component from moisture and containments. The degree of protection depends on the enclosure type. There are two categories of enclosures: open and totally enclosed. Open enclosures enable cooling air to flow through the motor. One type of open enclosure is the open drip proof enclosure. This enclosure has vents that allow for air flow. Fan blades attached to the rotor move air through the motor when turning.

The air surrounding the motor contains corrosive or harmful elements which can damage internal parts of motor. A totally enclosed non-ventilated (TENV) motor enclosure limits the flow air into the motor, but is not airtight. A seal at the shaft passes through the housing prevents water, dust, and other foreign matter from entering the motor along the shaft. All the heat inside the motor dissipates through the enclosure by conduction.

A totally enclosed fan-cooled (TEFC) as show in Figure 3.9 is the type enclosure used in this project. It is similar to TENV motor but has an external fan mounted opposite drive end of the motor. The fan blows air over the motor’s exterior for additional cooling. The fan is covered to prevent anyone from touching. This type of enclosure is commonly used and easy to find. Its can be used in dirty, moist, or mildly corrosive environment.

Figure 3.9: Type of enclosure used

Another type is Explosion proof motor. The appearance similar to TEFC motor but their enclosure is cast iron. The application used in hazardous location.

3.3 Assemble the motor part

The last step is assembling all the motor part like stator, rotor, enclosure, and bearing. These parts should have suitable by each other. Figure 3.10 shows all the part of motor that have been assembled.

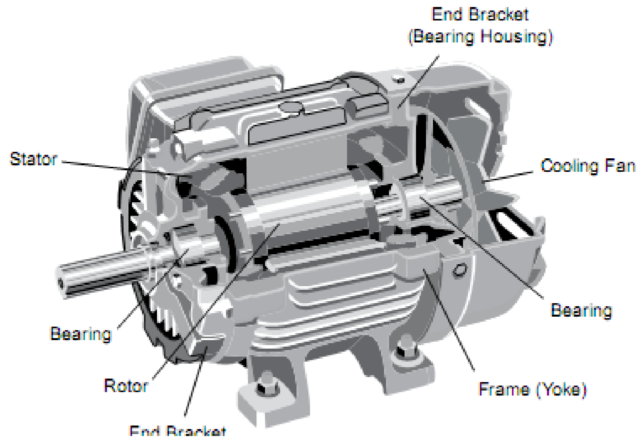


Figure 3.10: Part of motor that have been assembled

The size of bearing should compatible with bearing housing and diameter of the shaft. It's also same to the size of shaft. Shaft size should be according to the size of stator case. It's important because it will affect to the air gap. The large air gap contributes to high resistance to the passage of magnetic flux. The air gap needed to separate the revolving rotor from the stator should be as small as possible to reduce the magnetizing power requirement. The higher of the motor speed then the larger the air gap. For the induction machine, in power ratings from 3/4 to 750 kilowatts, practical values from 0.2 to 5 mm are typical. But for the synchronous machine air gaps is several times larger than those in induction motors.

3.4 Analysing motor output

In the analysis, the synchronous motor output is compared to the induction type motor with the same spec of 0.5hp. This can be done by replacing the synchronous motor shaft with induction motor shaft. This is because the construction of synchronous motor and induction motor are mostly same except at the rotor part. The synchronous motor using permanent magnet shaft and induction motor use squirrel cage rotor. A squirrel cage rotor is made by stacking thin steel lamination to form a cylinder. Figure 3.11 below shows squirrel cage type of rotor.